Mengistu *et al. Environ Syst Res (2017) 6:5*
DOI 10.1186/s40068-017-0079-4

Environmental Systems Research

RESEARCH **Open Access**

Comparative effectiveness of different composting methods on the stabilization, maturation and sanitization of municipal organic solid wastes and dried faecal sludge mixtures

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Abstract

Background: Composting is one of the integrated waste management strategies used for the recycling of organic wastes into a useful product. Composting methods vary in duration of decomposition and potency of stability, maturity and sanitation. This study was aimed to investigate the comparative effectiveness of four different methods of composting viz. windrow composting (WC), Vermicomposting (VC), pit composting (PC) and combined windrow and vermicomposting (WVC) on the stabilization, maturation and sanitization of mixtures of municipal solid organic waste and dried faecal sludge.

Methods: The composting treatments were arranged in a completely randomized block design with three replications. The changes in physico-chemical and biological characteristics of the compost were examined at 20 days interval for 100 days using standard laboratory procedures. The analysis of variance was performed using SAS software and the significant differences were determined using Fisher's LSD test at $P \leq 0.05$ level.

Results: The evolution of composting temperature, pH, EC, NH_4^+, NO_3^-, NH_4^+:NO_3^- ratio, OC, C:N ratio and total volatile solids varied significantly among the composting methods and with composting time. The evolution of total nitrogen and germination index also varied significantly ($P \leq 0.001$) with time, but their variation among the composting methods was not significant ($P > 0.05$). Except for PC, all other methods of composting satisfied all the indices for stability/maturity of compost at the 60th day of sampling; whereas PC achieved the critical limit values for most of the indices at the 80th day. A highly significant differences ($P \leq 0.001$) were noted among the composting methods with regard to their effectiveness in eliminating pathogens (faecal coliforms and helminth eggs). The WVC method was most efficient in eliminating the pathogens complying with WHO's standard.

Conclusion: Turned windrow composting and composting involving earthworms hastened the biodegradation process of organic wastes and result in the production of stable compost earlier than the traditional pit method of composting. The WVC method is most efficient in keeping the pathogens below the threshold level. Thus, elimination of pathogens from composts being a critical consideration, this study would recommend this method for composting organic wastes involving human excreta.

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Keywords: Composting, Faecal coliform, Faecal sludge, Helminth egg, Municipal solid waste, Maturation, Sanitization, Stabilization, Vermicomposting

Background

As in many other cities of the developing countries, the rapid urbanization and high population growth of Dire Dawa (Ethiopia's 2nd largest city) have resulted into a significant increase in generation of wastes from domestic and commercial activities, posing numerous questions concerning the adequacy of the current waste management systems, and their associated environmental, economical and social implications. A report by Beneberu et al. (2012) depicted that, despite the great efforts made by the Dire Dawa city municipality, it has been hardly possible to meet the ever-increasing waste management service demand of the city adequately and effectively. The per capita waste generation rate of the city is reported to be 0.3 kg day^{-1} and the city generates an estimated quantity of 77 tonnes of solid wastes per day (Community Development Research 2011). The same report indicated that, as there is very limited or no effort to recycle, reuse or recover the waste that is being generated; waste disposal has been the major mode of waste management practice. It has been observed that the indiscriminate dumping of wastes into the landfill is resulting in unexpectedly faster filling up of the city's sanitary landfill which would, thus, likely be abandoned in the near future than anticipated 30 years (Beneberu et al. 2012).

In addition to the municipal solid wastes (MSW), the human excreta also constitute a significant component of wastes generated from Dire Dawa city. Faecal sludge (FS) accumulating in the commonly used on-site sanitation systems are periodically collected and dumped indiscriminately into its well-engineered sludge dewatering and drying bed. The faecal sludge, after being dried in the beds, since it has no purpose in Dire Dawa, was observed to be excavated from the drying beds and disposed in the landfill site. It is, therefore, of paramount importance to establish economically viable, environmentally sustainable and socially acceptable method of waste management for the sustainable development of the city.

Bundela et al. (2010) suggested that agricultural application of organic solid wastes, as nutrient source for plants and as soil conditioner, is the most cost effective municipal solid waste (MSW) disposal option because of its advantages over traditional means, such as land filling or incineration. Though, human wastes are a rich source of organic matter and inorganic plant nutrients and therefore used to support food production, their use without prior stabilization represents a high risk because of the potentially negative effects of any phytotoxic substances or pathogens they may contain (Garcia et al. 1993). Application of raw wastes may inhibit seed germination, reduce plant growth and damage crops by competing for oxygen or causing phytotoxicity to plants due to insufficient biodegradation of organic matter (Brewer and Sullivan 2003; Cooperband et al. 2003). Moreover, the reuse of untreated faeces for agricultural purposes can cause a great health risk, because a great number of pathogens such as bacteria, viruses and helminthes can be found in human excreta (Gallizzi 2003). Therefore, the management of urban solid wastes involving human excreta for recycling in agriculture should necessarily incorporate sanitization, stabilization and maturation aspects to minimize potential disease transmission and to obtain a more stabilized and matured product for application to soil (Carr et al. 1995).

Composting and vermicomposting are two of the best-known processes for biological stabilization of solid organic wastes by transforming them into a safer and more stabilized material that can be used as a source of nutrients and soil conditioner in agricultural applications (Lazcano et al. 2008; Bernal et al. 2009; Domínguez and Edwards 2010). Composting involves the accelerated degradation of organic matter by microorganisms under controlled conditions, in which the organic material undergoes a characteristic thermophilic stage that allows sanitization of the waste by elimination of pathogenic microorganisms (Lung et al. 2001). Vermicomposting, on the other hand, is emerging as the most appropriate alternative to conventional aerobic composting (Yadav et al. 2010) and it involves the bio-oxidation and stabilization of organic material by the joint action of earthworms and microorganisms (Lazcano et al. 2008). More recently, combining thermophilic composting and vermicomposting has been considered as a way of achieving stabilized substrates (Tognetti et al. 2007). Thermophilic composting results in sanitization of wastes and elimination of toxic compounds while the subsequent vermicomposting reduces particle size and increases nutrient availability (Mupondi et al. 2010).

Composting methods differ in duration of decomposition and potency of stability and maturity (Iqbal et al. 2012). Due to the ecological and health concerns of human wastes, extensive research has been conducted to study the composting process and to evaluate methods to describe the stability, maturity and sanitation of compost prior to its agricultural use (Brewer and Sullivan 2003; Zmora-Nahum et al. 2005). Although several studies have addressed the optimization of composting, vermicomposting or composting with subsequent vermicomposting of various organic wastes (Dominguez et al. 1997; Frederickson et al. 1997; Ndegwa and Thompson 2001; Tognetti et al. 2005, 2007; Lazcano et al. 2008; Mupondi et al. 2010), information on the effectiveness of the different composting methods on biodegradation and sanitization of mixtures of MSW and dried faecal sludge (DFS) is scant. Moreover, regarding the sanitization efficiency of the different composting techniques, controversial reports have been presented in different literatures. Several researchers reported the effectiveness of thermophilic composting in eliminating pathogenic organisms (Koné et al. 2007; Vinnerås 2007; Mupondi et al. 2010). However, a few studies on composting of source-separated faeces claimed that a sufficiently high temperature for pathogen destruction is difficult to achieve (Bjorklund 2002; Niwagaba et al. 2009). Similarly, in vermicomposting, some studies have provided evidence of suppression of pathogens (Monroy et al. 2008; Rodriguez-Canche et al. 2010; Eastman et al. 2001), while others (Bowman et al. 2006; Hill et al. 2013) demonstrated the insignificant effect of vermicomposting in reducing *Ascaris summ* ova as compared to composting without worms. The effectiveness of vermicomposting for pathogen destruction was still remaining unclear due to conflicting information in the literature (Hill et al. 2013); the present scenario thus, calls for further exploration. Accordingly, the present study attempted to investigate the comparative effectiveness of four different methods of composting viz. windrow composting (WC), Vermicomposting (VC), pit composting (PC), and combined windrow and vermicomposting (WVC) on the stabilization, maturation and sanitization of mixtures of MSW and dried faecal sludge.

Methods

Experimental site, wastes and earthworms utilized

The study was carried out at Dire Dawa, a city in Eastern Ethiopia located at 9° 6′ N, 41° 8′ E and at an altitude of 1197 m above sea level. The Municipal solid organic waste used in this study was obtained from a door-to-door waste collection service provided by the Sanitation and Beautification Agency (SBA) of Dire Dawa city, in which the wastes were collected from various locations in the city. The dried faecal cake which was about to be excavated from the drying bed and dumped to the landfill site was collected from the dumping site. The garbage receives mixed organic and inorganic domestic wastes, upon arrival to the composting site; the wastes were spread flat on the ground and sorted manually into organic and non-organic fractions. All the compostable components were shredded manually into small pieces of particle sizes ranging from 3 to 5 cm as described by Pisa and Wuta (2013). The shredded MSW and dried faecal sludge were then mixed manually in a 2:1 mix ratio. The earthworm species (*Eisenia foetida*) were obtained from Haramaya University. Matured earthworms and their cocoons were brought to Dire Dawa, where they were made to be multiplied (reared) for about 4 months using cow dung as medium.

Composting treatments

The methods of composting tested were: turned windrow composting (WC), pit composting (PC) (a composting method commonly practiced by farmers of the study area), vermicomposting (VC) and combined windrow and vermicomposting (WVC). The composting was done in outdoor but under shade condition. Three replicates of each of the four composting methods were made being arranged in a completely randomized block design. Each composting pile was covered with a layer of dry grass (5 cm) to prevent excessive loss of moisture.

a) *Windrow composting*: In the thermophilic composting, the homogenized feedstock of 1 m^3 volume (~275 kg dry weight) was heaped into conical piles in about 1 m^2 area after being wetted with water to 50–60% (Maso and Blasi 2008).
b) *Pit composting* a homogenized feedstock with the same moisture level as in ‘a’ was filled in a pit with dimension of 1 × 1 × 1 m (length width and depth).
c) *Vermicomposting*: Vermicomposting was performed in vermicompost bed measuring 1 × 1 × 0.3 m (length, width and height respectively) framed with bricks where the walls and bottom of the structure was lined with polyethylene sheet. In order to drain the excess water, the bottom of the polyethylene sheet was made to have tiny holes. Mature earthworms (*E. foetida*) were introduced at the recommended stocking rate of 250 adult worms per 20 kg of bio-waste (Padmavathiamma et al. 2008). The moisture content of the material was maintained between 70 and 80% (Maso and Blasi 2008).
d) *Combined windrow composting and vermicomposting*: Thermophilic composting of the wastes was done in same manner as in windrow composting and the piled substrate was allowed to be composted until the temperature was dropped to mesophilic phase. After the completion of the thermophilic phase (15 days after the initiation of the process), the subsequent vermicomposting continued using earthworms (*E. foetida*) as described under vermicomposting (Mupondi et al. 2010**)**.

The pilled heaps in WC were turned and mixed every week while the substrates in other methods of composting were left intact. The moisture content of each pile was checked every week and adjusted accordingly. The compost mass in WVC received the same treatment as WC and VC during the thermophilic and mesophilic phases of composting respectively. The temperatures in each heap was measured daily with a temperature probe from randomly selected places (centre, bottom and top) throughout the process.

Compost sampling and analysis

Sampling procedure

To evaluate the various physical, chemical and biological transformations of the compost, representative samples were collected from four different points of the compost pile (bottom, surface, side and centre) of each pile at every 20 days (20, 40, 60, 80 and 100 days). All the samples were sealed in plastic containers and transported immediately to the laboratory using an ice box. Up on their arrival to the laboratory, the samples were stored in a refrigerator at 4 °C until they were analysed. Physico-chemical and microbial analyses were carried out at Haramaya University following standard procedures.

Physico-chemical analysis of compost

Moisture content was determined as weight loss upon drying in an oven at 105 °C to a constant weight (Lazcano et al. 2008). Total nitrogen (TN) and organic carbon (OC) were determined using dried compost samples which were ground to pass through a 2-mm sieve as described by Pisa and Wuta (2013). For the determination of total N, samples were decomposed using concentrated H_2SO_4 and catalyst mixture in Kjeldahl flask and subsequently, N content in the digest was determined following steam distillation and titration method (Bremner and Mulvaney 1982). Organic carbon was estimated by dichromate wet digestion and rapid titration methods as described by Walkley and Black (1934). Total volatile solids was determined as weight loss on ignition at 550 °C for 4 h in a muffle furnace as described by Lazcano et al. (2008). Ammonium N (NH_4^+–N) was determined from 0.2 ml aliquot of 0.5 M K_2SO_4 extract of the filtrate after colour development with sodium nitroprusside, whereas, Nitrate N (NO_3^-–N) was determined in a separate aliquot (0.5 ml) after colour development with 5% salicylic acid using a spectrophotometer (Okalebo et al. 2002). Analysis for pH and electrical conductivity (EC) were performed in extracts of 1:10 (w/v) compost: distilled water ratio as described by Ndegwa and Thompson (2001). The C:N ratio was calculated using the individual values of OC and TN.

Compost phytotoxicity test

For determining compost phytotoxicity, a modified phytotoxicity test employing seed germination was used (Zucconi et al. 1981). A 10 g of screened compost sample was shaken with 100 ml of distilled water for an hour, then the suspension was centrifuged at 3000 rpm for 15 min and the supernatant was filtered through a Whatman No 42 filter paper. Number 2 Whatman filter paper was placed inside a sterilized petri dish and wetted with 9 ml of the extract, 30 tomato seeds (*Solanum esculentum* L.) were placed on the paper. Nine ml of distilled water was used as a control and all experiments were run in triplicate (Wu et al. 2000). The petri dishes were kept in the dark for 4 days at room temperature. At the end of the 4th day, the germination index (GI) was calculated using the following formula (Selim et al. 2012).

$$\text{Germination Index (\%)} = \frac{\text{Seed germination (\%)} \times \text{root elongation (\%)}}{100}$$

Faecal coliform analysis

For the determination of faecal coliforms in the initial raw materials and in the composts the procedures described by Mupondi et al. (2010) were employed. Aseptically weighed 10 g samples of either waste mixture or fresh compost were added to 90 ml of distilled water previously autoclaved at 121 °C for 15 min and the suspensions were then mixed using a blender to ensure thorough mixing. Additional serial dilutions were made up to 10^{-6}. A 0.1 ml aliquot of each dilution was plated, in triplicate, in appropriate media-Violet Red Bile Agar (VBA) (Vuorinen and Saharinen 1997). The plates were then maintained in an incubator at a constant temperature of 44 °C for 24 h. For each of the treatment samples the numbers of faecal coliforms were expressed as $\log_{10}$ CFU (colony forming unit) per gram of fresh sample and average values were calculated.

Helminth eggs recovery

The determination of helminth egg in this study was done based on the US EPA protocol (1999) modified by Schwartzbrod (2003). The analysis was carried out in triplicate for the initial raw waste and compost samples. The concentration of number of eggs per gram of dry weight of sample was computed according to the following formula (Ayres and Mara 1996):

$$\mathrm{N} = \frac{\mathrm{Y}}{\mathrm{C}} \times \frac{\mathrm{M}}{\mathrm{S}},$$

where N = number of eggs per gram of dry weight of sample, Y = number of eggs in the McMaster slide (mean of counts from three slides), M = estimated volume of product at final centrifugation, C = volume of the McMaster slide, S = dry weight of the original sample.

Data analysis

The data obtained from this study were subjected to statistical analysis of variance (ANOVA) procedures using SAS software and the significant differences were determined using Fisher's LSD test at $P \leq 0.05$ level.

Results and discussion

Characteristics of the raw waste materials

The results of the analysis for the raw wastes are presented in Table 1. The pH of the municipal solid waste (MSW) was alkaline and that of dried faecal sludge (DFS) was acidic in reaction. EC of MSW was much greater than that of DFS. The alkaline pH and high EC value in MSW could be attributed to the presence of wood ash which was observed to occur in considerable amount during the screening of the waste. The total N content of DFS was more double than that of MSW, indicating that it could be used to reduce the C:N ratio of the MSW.

The total helminth egg count for the dried faecal sludge and mixture of faecal sludge and MSW was 80.56 g^{-1} TS and 38.89 g^{-1} TS respectively, which is far greater than the recommended value for materials used in agriculture as per WHO's guidelines (≤3–8 eggs g^{-1} TS) (Xanthoulis and Strauss 1991). Similarly, the total faecal coliform count of all the raw materials was found to exceed the standard threshold limit of <1000 cfu g^{-1} (WHO 2006). Therefore, it suggests that the raw wastes cannot be used directly for agriculture without being treated as it may result in soil contamination. The germination index values of the wastes was also far below the standard limit (>80%) substantiating the presence of phytotoxic substances which would make the raw wastes unfit for application in agricultural soils (Additional file 1: Table S1).

Evolution of composting temperature

Considerable variations in temperature conditions were observed among the different composting methods on course of the composting period (Fig. 1). Though there were series of rise and fall in temperature, the general pattern of temperature for treatments (particularly for WC and PC) was similar. There was a rapid rise in temperature during the first few days of the composting process followed by a fall with time and finally it began to gradually reach to the ambient temperature. These temperature patterns denoted the thermophilic, mesophilic and maturation phases of a composting process, respectively. The rapid progress from initial mesophilic phase to thermophilic phase in WC and PC indicates a high proportion of readily degradable substances and self-insulating capacity of the waste (Sundberg et al. 2004). The change in temperature pattern observed in this study is in accord with other composting study (Tognetti et al. 2007).

Temperatures reached the thermophilic range (>45 °C) on the second and third day for the WC and PC which lasted for 15 and 19 days, respectively after initiation of the process. During these days of the process, a higher temperature was recorded for the WC than the PC. A peak average temperature ranging between 60.7 and 62.67 °C was recorded during the 3rd to 6th days for WC. Correspondingly for PC, the highest average temperature of 50.2–52.4 °C was registered during the 3rd to 9th day (Additional file 1). The increase in temperature

Table 1 Mean values ± standard error of the chemical and biochemical properties in the initial raw wastes used in the study

Chemical and bio-chemical property	Raw material		
	MSW	DFS	MSW:DFS (2:1)
pH	7.39 ± 0.02	6.34 ± 0.02	6.67 ± 0.01
EC (μs/m)	2233 ± 55.87	1258.67 ± 70.99	1583 ± 7.94
Total N (g kg^{-1})	10.08 ± 0.16	26.23 ± 0.09	15.59 ± 0.19
Total OC (g kg^{-1})	308.13 ± 1.65	299. 38 ± 2.25	301.88 ± 1.08
C:N ratio	30.58 ± 0.33	11.42 ± 0.08	19.37 ± 0.17
TVS (g kg^{-1})	559.81 ± 2.36	506.38 ± 6.28	523.40 ± 8.09
NH_4^+ (mg kg^{-1})	479.15 ± 7.074	1943.02 ± 39.45	1014.27 ± 37.25
NO_3^- (mg kg^{-1})	184.68 ± 3.696	1875.43 ± 36.81	684.53 ± 7.90
NH_4^+:NO_3^- ratio	2.595 ± 0.024	1.04 ± 0.02	1.48 ± 0.07
Germination Index	6.475 ± 0.48	42.06 ± 1.27	31.84 ± 1.58
Faecal coliforms (log_{10} cfu)	4.59 ± 0.01	4.73 ± 0.03	4.63 ± 0.04
Helminth egg g^{-1} TS	–	80.55 ± 4.81	38.88 ± 1.60

MSW municipal solid waste, *DFS* dried faecal sludge, *OC* organic carbon, *EC* electrical conductivity, *TVS* total volatile solids, *cfu* colony forming units, *TS* total solids

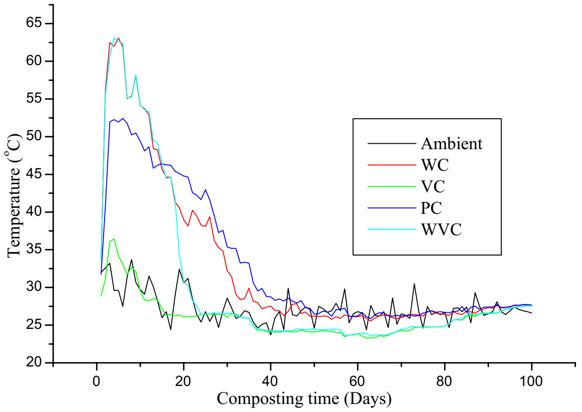

Fig. 1 Changes in ambient air temperature and temperature in the experimental piles during the composting process (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting)

within the composting mass was caused when the heat generated from the respiration and decomposition of sugar, starch and protein by the population of microorganisms accumulates faster than it is dissipated to the surrounding environment (Jusoh et al. 2013).

During the subsequent mesophilic phase (45–35 °C), however, PC registered a relatively higher temperature than WC. This phase was lasted for 13 days, from 16th to 28th day for WC and from 20th to 32nd day for PC and from the respective days on temperature values <35 °C and very close to the ambient temperature was recorded for both composting methods. The ambient temperature during the experimental period ranged from 23.7 to 33.7 °C (Fig. 1).

The vermicomposting unit (VC), where low temperature was induced intentionally by spreading the material in ground beds, tended to show the lowest temperature all through the process. The temperature profile for the WVC during the thermophilic phase showed similar pattern as that of the WC and has taken a different track during the subsequent vermicomposting process resembling the sole vermicomposting unit.

The size, initial moisture content and aeration of the piled substrate might have attributed for the variation in temperature of the different composting methods. Initially, to protect the earthworms from extreme thermophilic temperature and to keep an optimum condition for their performance, the height and moisture content of the pile in the vermicomposting unit were maintained to 30 cm and 80% compared to 1 m height/depth and 60%, respectively, in the WC and PC piles. As a result, the vermicompost with small volume of organic pile and relatively high moisture content does not heat up as such because the heat generated by the microbial population is lost quickly to the atmosphere, whereas in the WC and PC heat build-up particularly in the centre of the pile might have been insulated by the outer layer letting the temperature inside the pile to be raised. It is a well-established fact that, the smaller the bioreactor or compost pile, the greater the surface area-to-volume ratio, and therefore the larger the degree of heat loss to conduction and radiation (http://www.cfe.cornell.edu/compost/invertebrates.html).

The possible explanation for the variation in temperature profile of the WC and PC, given the same volume and moisture content of the pile, may be the differences in aeration (air circulation) in the piled substrates. The weekly turning of the compost mass in WC might have promoted the free circulation of air to enhance the microbial activity in the oxidation process and thereby raise the temperature; whereas in PC, the substrates being stacked in the pit without being turned the circulation of air in the pile might have been relatively restricted to impair the microbial activity and thereby the heat generated during the process. Finstein et al. (1986) who demonstrated the linear relationship between the oxygen consumed and heat produced during aerobic metabolism, support the finding of this study.

Evolution of pH

The first pH reading being taken at the 20th day after the initiation of the process, a sharp and significant ($P \leq 0.001$) rise in pH than the initial state was observed in all the treatments. The rise in pH during these days is considered to be the result of the metabolic degradation of organic matter containing nitrogen (proteins, amino acids etc.) leading to formation of amines and ammonia salts through mineralization of organic nitrogen (Dumitrescu et al. 2009). As Smith and Hughes (2002) and Mupondi et al. (2006) suggested, it might also be attributed to the decomposition of organic acids to release alkali and alkali earth cations previously bound by organic matter. An increase in pH during composting of different substrates was also reported in many other studies (Sundberg et al. 2004; Tognetti et al. 2007; Gao et al. 2010).

The analysis of variance (ANOVA) showed a non-significant variation ($P > 0.05$) of pH values among the different methods of composting at the 20th day of sampling. Nevertheless, as composting progressed, significant variation ($P \leq 0.01$) in pH was noted among the different composting methods (Fig. 2). Except for PC, which exhibited a further rise in pH, all other methods of composting showed a fairly stable pH during the 20th to 60th day of the process. This was followed by a slight fall to nearly neutral pH value during 80th to 100th day. In PC, a rise in pH value was observed to extend to the 60th

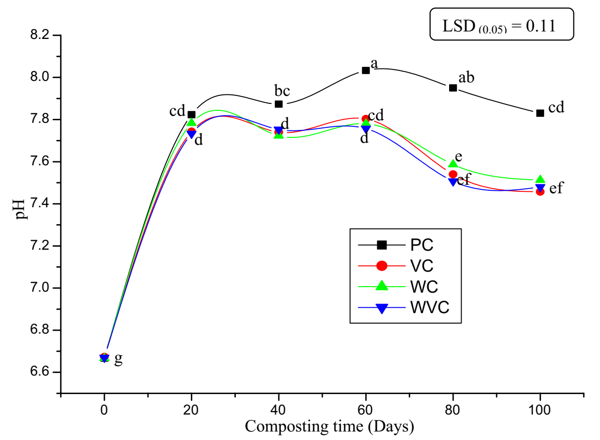

Fig. 2 Changes in pH in different composting methods with time. (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting, *LSD* least significant difference). *Different letters* indicate significant differences at P ≤ 0.05

day (8.03), after which it declined slightly at the 80th day and finally dropped to 7.83 at the 100th day.

Generally, from the 20th day till the end of the process (100th day), PC registered the highest pH value than the rest of the composting methods which were noted for their statistical parity (P > 0.05) (Fig. 2). This may possibly be caused due to the relatively higher concentration of ammonium ion maintained in PC. The relative decline in pH during the latter stage of the composting process might be caused due to the nitrification process which is responsible for the release of H^+ ion (Huang et al. 2001). This is also evident from NO_3^- data which was observed to increase remarkably during later stages of the process. Overall, the pH values achieved in all treatments at the end of the experiment were within the range acceptable for plant growth as recommended by Tognetti et al. (2005).

Evolution of electrical conductivity (EC)

The electrical conductivity values varied significantly (P ≤ 0.01) among the composting methods and over the different composting period. Generally, as indicated in Fig. 3, all the treatments showed similar pattern of change in EC where the value decreased steadily with the progress in the composting process. It was found to be reduced by about 55.53, 54.66, 47.97, and 37.40% respectively for VC, WVC, PC, and WC at the 100th day as compared to the initial value of the raw material at day 0. The obtained results are in agreement with Yadav et al. (2012) and Gao et al. (2010) who reported an eventual decrease in EC value with progress in composting and vermicomposting. However this is in contrast with other studies (Gómez-Brandón et al. 2008) which reported increased EC values with composting time.

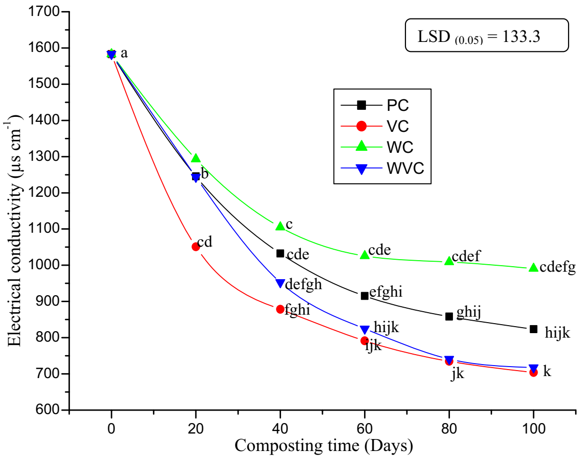

Fig. 3 Changes in EC in composting mixtures of different composting methods with time. (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at P ≤ 0.05

The progressive decline of EC value with time would justify that, firstly; there might be leaching of mineralized ions during periodic showering of water on the composting mass, secondly; as composting process progressed, humification would inevitably proceed and the resulting humic fractions might have complexed the soluble salts which in turn tend to decrease the amount of mobile free ions and thereby the EC (Rao 2007).

The ANOVA results revealed that the EC value during the entire composting period was significantly higher (P ≤ 0.001) for WC followed by PC, whereas VC which was in statistical parity with WVC recorded the lowest value (Fig. 3). This would justify that the piled substrates in PC, VC and WVC which were not turned, but rather watered periodically on top to maintain the moisture at optimum; the soluble ions might have gradually been leached down. Moreover in VC and WVC, owing to the smaller size of the pile and a relatively large quantity of water added, the leaching of those ions might have been even more pronounced than the PC. In WC on the other hand, the weekly turning and mixing up of the substrate might have helped the redistribution of the mineralized ions in the compost mass and hence the loss of those ions from the system through leaching might have relatively been reduced. This finding is in line with Lazcano et al. (2008) and Frederickson et al. (2007) who reported a significantly lower EC value for VC and WVC than WC. The EC value in the final product of all treatments was far below the threshold value of 3000 µS cm^{-1} indicating a material which can be safely applied to soil (Soumaré et al. 2002).

Evolution of total organic carbon

With advancement of the composting process, the total organic carbon content of the compost decreased consistently and significantly ($P \leq 0.01$) for all the treatments (Fig. 4). The decrease in organic carbon content at the end of the composting process with respect to WVC, VC, WC and PC was 54.74, 54.52, 52.00, and 48.80%, respectively of their initial carbon content. The present finding is also in consent with the findings of Tiquia et al. (2002), who reported a total carbon loss that ranged from 50 to 63% in turned windrows and 30–54% in unturned windrows. Similarly, reviewing the works of other authors, Yadav et al. (2010) reported total organic carbon reduction values ranging between 26 and 66% during vermicomposting of wastes of various sources. The variation in the amount of OC lost from the different composting method may possibly be caused by differences in the aeration of the piled substrate. Turning the compost pile (in WC) and continuous borrowing and fragmenting of the material by earthworms (in VC and WVC) might have altered the aeration of the compost mass and accelerated the degradation process to enhance the loss of carbon as carbon dioxide. The results are in agreement with the findings of Guo et al. (2012) who demonstrated higher losses of carbon in treatments receiving higher rates of aeration.

Evolution of total nitrogen

Changes in the total nitrogen of the different composting methods varied significantly ($P \leq 0.01$) with the different sampling period, while the variation among the composting methods was found to be statistically insignificant ($P > 0.05$) (Fig. 5). The total nitrogen content of the initial raw material of all treatments was reduced significantly ($P \leq 0.01$) during the first 20 days of composting. However, during the subsequent sampling, there was a gradual increment of total nitrogen, the maximum value being recorded at the 100th day. The decline in the total nitrogen during the first 20 days might be attributed to the loss of nitrogen in the form of ammonia which is apparent during the active phase of composting. Witter and Lopez-Real (1988) reported nitrogen losses that could amount to 50% and considered that nearly all nitrogen lost is due to ammonia volatilization.

The rise in total nitrogen after the 20th day may be caused due to a concentration effect that resulted from degradation of organic C compounds which in turn leads to weight loss and therefore, a relative increase of N concentration (Dias et al. 2010). As Bernal et al. (1998) explained the concentration of N usually increases during composting when the loss of volatile solid (organic matter) is greater than the loss of NH_3. This would generally indicate that there was a relatively greater increase in total N compared with the decrease in the organic carbon content. The results of the present study would, therefore, justify that during the first 20 days of composting, losses of N through NH_3 volatilization occurred at a greater rate than organic matter degradation, while during the subsequent periods, the rate of N loss as NH_3 might be slower than the rate of dry matter loss as CO_2. In addition, the N level might have also been increased due to the fixation of atmospheric N within the compost heap by the free living N fixing microorganisms' activity that commonly occurs during the later stage of the composting process (Seal et al. 2012). In their co-composting

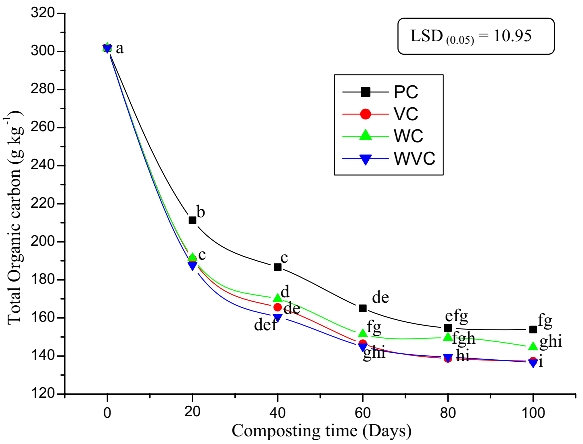

Fig. 4 Changes in total organic carbon in composting mixture of different composting methods with time. (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at $P \leq 0.05$

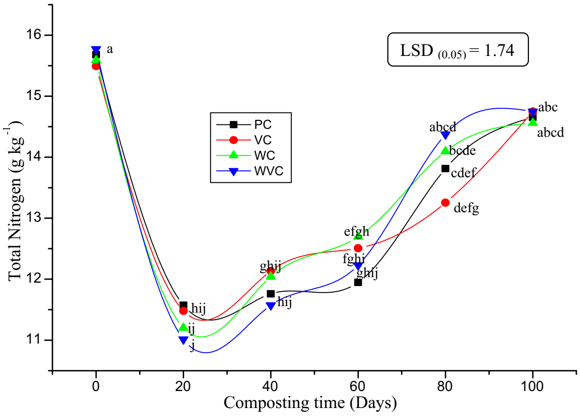

Fig. 5 Changes in total nitrogen in composting mixture of different composting methods with time (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at $P \leq 0.05$

study of pig manure and corn stalks, Guo et al. (2012) reported results that were in agreement with the trends of the present study—a general decrease of total nitrogen during the thermophilic phase followed by an increase then after.

Evolution of C:N Ratio

The C:N ratio of the composting material of all the treatments narrowed consistently and significantly ($P \leq 0.01$) with the advancement of the composting time (Fig. 6). The initial C:N ratio of the raw material at day 0 was 19:1 which was within the recommended range suitable for composting (35–12) (Epstein 1997). This was found to decrease to nearly 11:1, 9:1, 10:1 and 9:1 at the 100th day of sampling for PC, VC, WC and WVC, respectively. Obviously, throughout the composting process the organic matter is decomposed by microorganisms through which the organic carbon was oxidized to CO_2 gas to the atmosphere and thus lowers the C:N ratio (Jusoh et al. 2013). This is in conformity with the findings of other studies (Kumar et al. 2009; Khwairakpam and Kalamdhad 2011).

C:N ratio value for PC was significantly ($P \leq 0.01$) higher than the other methods of composting which were statistically at par ($P > 0.05$) with each other (Fig. 6). The variation seemed to arise mainly due to the differences in the amount of total organic carbon as could be witnessed from previous discussion and the same justification given above can also be claimed for the variation in C:N ratio among the different composting methods. Generally, the C:N ratios in the final product of all the treatments were found to be satisfactory because matured compost material usually has a C:N ratio of 15 or less (Hock et al. 2009).

As Gómez-Brandón et al. (2008) pointed out C:N ratio may not be a good indicator of compost stability because it can level off before the compost stabilizes. When wastes rich in nitrogen are used as source material for composting, the C:N ratio can be within the values of stable compost even though it may still be unstable. By the same token, Zmora-Nahum et al. (2005) reported a C:N ratio lower than the cut-off value of 15 very early during the composting of cattle manure, while important stabilization processes were still taking place. Correspondingly, in the present study, three of the four treatments (VC, WVC and WC) and PC achieved a C:N ratio of <15 at the 40th and 60th day of sampling, respectively, while the degradation of the organic material was still significant till the 60th and 80th days for the respective treatments. As evidenced earlier a statistically stable values for total organic carbon was observed during the 60th to 100th and 80th to 100th day of sampling for the respective treatments.

Evolution of NH_4^+, NO_3^- and NH_4^+:NO_3 ratio

The concentration of NO_3^-–N and NH_4^+–N varied significantly ($P \leq 0.001$) for the different composting methods and over the different composting period, notwithstanding that all the treatments have generally shown similar pattern of changes in both ammonium and nitrate concentrations (Figs. 7, 8). As can be seen from the graph (Fig. 7), all the composting methods showed a rise in NH_4^+–N concentration during the 20th day of sampling which was then declined sharply as evidenced at the 40th day and coming to decrease slightly from the 40th day until the end of the experiment (100th day).

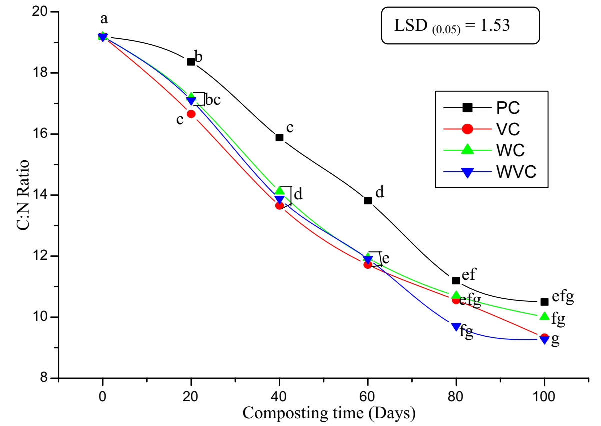

Fig. 6 Changes in C:N ratio of composting mixture in different composting methods with time (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at $P \leq 0.05$

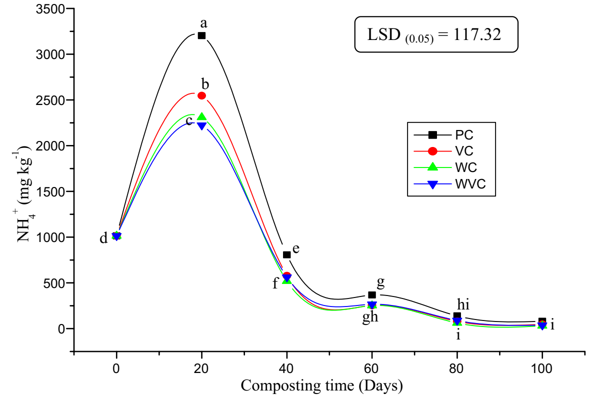

Fig. 7 Changes in NH_4^+ concentration of composting mixture in different composting methods with time (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at $P \leq 0.05$

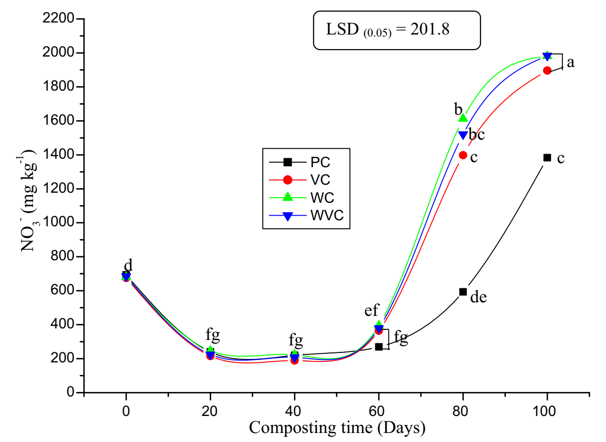

Fig. 8 Changes in NO_3^- concentration of composting mixture in different composting methods with time (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at $P \leq 0.05$

The rise in NH_4^+–N concentration during the first 20 days was likely to be caused as a result of the mineralization of organic matter (the conversion of organic N to NH_4^+ via the ammonification process), thus reflecting active transformation of organic matter and unstable substrate (Tognetti et al. 2005; Guo et al. 2012). Whereas the decrease in NH_4^+–N during the subsequent sampling periods was probably due to NH_3 volatilization (Gao et al. 2010), the microbial immobilization as nitrogenous compounds such as amino acids, nucleic acids and proteins and/or its oxidation to NO_3^- through nitrification process (Guo et al. 2012). An increase in NH_4^+–N concentration during the initial stage of composting and its reduction afterwards was reported by Gao et al. (2010).

The analysis of variance indicated that PC registered the highest concentration of NH_4^+–N during all the sampling period. However, a statistically significant ($P \leq 0.01$) variation of NH_4^+–N among the treatments was recorded only at the 20th and 40th day of sampling (Fig. 7). Turning the piled substrate in WC and the smaller size and increased surface area of the vermibed in VC and WVC might have resulted in increased loss of ammonia leading to a relatively low level of ammonium at this day of sampling (20th day). The compost pile in PC, on the other hand, being not turned and mixed, the loss of N in the form of ammonia might have relatively been reduced and this might have contributed for the increased level of ammonium nitrogen in PC than the other methods of composting. Similar results were reported by Guo et al. (2012) who noted highest level of ammonium nitrogen in treatments with low than high aeration rate.

Regarding the NO_3^-–N, for all the treatments its level was sharply and significantly ($P \leq 0.01$) decreased at the 20th day sampling than the initial. This might be caused due to either the leaching of nitrate by water during periodic watering of the composting mass or its immobilization by the decomposing microorganisms. During the subsequent composting period (20th to 60th days), however, the NO_3^-–N level came to be relatively stable and during these days the variation in NO_3^-–N level among all the treatments was insignificant ($P > 0.05$) (Fig. 8). This was followed by a sharp rise of NO_3^-–N after the 60th day (for WC, VC and WVC) and 80th day (for PC) as evidenced on the 80th and 100th day of sampling, respectively. At the end of the process (100th day), PC exhibited a significantly lower value of NO_3^-–N than the other methods of composting. It seems that due to the better aeration by earthworms (in VC and WVC) and turning of the piles (in WC), the oxidation of NH_4^+ to NO_3^- might have been enhanced in the respective methods of composting than in PC.

The NH_4^+–N content of the starting material was clearly higher (1014.28 mg kg^{-1}) than the NO_3^-–N content (684.5 mg kg^{-1}), giving the NH_4^+:NO_3^- ratio to be 1.48. On course of the composting process the ratio was found to be raised sharply at the 20th day of sampling for all the treatments. This is followed by a drastic decline during the 40th day and coming to be declining gradually during the subsequent periods of composting (60–100 days) (Fig. 9). PC registered the highest ratio during all the sampling periods; however, a statistically

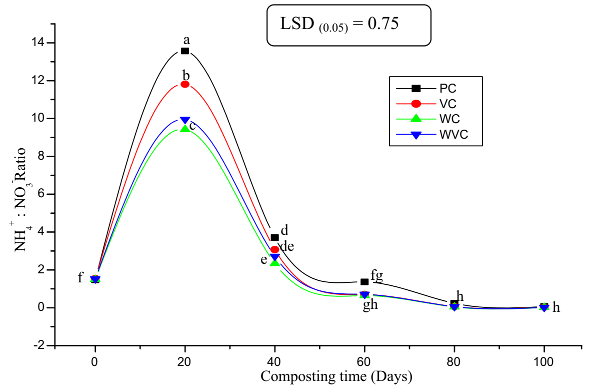

Fig. 9 Changes in NH_4^+:NO_3^- ratio of composting mixture in different composting methods with time (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at $P \leq 0.05$

significant variation among the composting treatments was noted only at the 20th and 40th day of sampling (Fig. 9). At the 20th day, the highest (13.57) and lowest (9.42) ratio was recorded for PC and WVC, respectively. At the 100th day of sampling the value was found to drop to 0.06, 0.026, 0.016 and 0.02, respectively for PC, VC, WC and WVC.

Critical limit values of <400 mg kg^{-1} for NH_4^+–N (Zucconi and de Bertoldi 1987), >300 mg kg^{-1} for NO_3^-–N (Forster et al. 1993) and <1 for NH_4^+-:NO_3^- ratio (Brewer and Sullivan 2003) has been established as a stability/maturity indices for composts of various origins. Concomitantly, except for PC all the other composting treatments satisfied the critical limits for stability/maturity at the 60th day of sampling. Whereas, PC achieved these values(NO_3^- –N and NH_4^+:NO_3^- ratio) at the 80th day, implying that PC was late to achieve the index value for maturity than the other three methods of composting and the same explanation given above pertaining to differences in aeration would also be suggested for the variation in these values among the treatments.

Evolution of total volatile solids (TVS)

The average total volatile solid (TVS) content of the raw waste was 523.4 mg kg^{-1} which steadily decomposed throughout the experimental period. The change in TVS with composting time showed the same pattern as the change in total organic carbon in that it decreases significantly ($P \leq 0.01$) with the advancement of composting time. The greatest reduction in TVS was noted during the first 20 days of composting signifying the fast degradation of the substrate during this active phase of composting (Fig. 10). The decrease in TVS content of the sample indicates the degradation of organic matter of the waste during the composting process (Levanon and Pluda 2002). Values of TVS varied significantly ($P \leq 0.01$) among the different methods of composting (Fig. 10). On the course of composting, the highest and lowest values of TVS were recorded for PC and WVC, respectively.

The analysis of variance revealed that the values of TVS for the three methods of composting (WC, VC and WVC) after the 60th day was insignificant ($P > 0.05$) indicating the stability of the product at the 60th day. Whereas, for PC a statistically stable value was achieved at the 80th day of composting, implying the relatively longer period of time the latter has taken for the product to be stable. This is due to the relatively slow rate of degradation of the organic matter in PC. The important role played by the earthworms in reducing the TVS through degrading wastes was reported by Yadav et al. (2012).

Phytotoxicity assessment

All the composting treatments followed the same general pattern of changes in germination index (GI) over the different sampling period and the variation in GI values among the treatments was insignificant ($P > 0.05$; Fig. 11). However, the values varied significantly ($P \leq 0.01$) with the composting time. The lowest value of this variable was recorded at the 20th day of sampling which was of course statistically not different from the starting material (day 0). This was observed to increase with the advancement of composting period up to the 60th day and from the 60th day on it came to a more or less stable value with insignificant variation (Fig. 11). Tiquia and

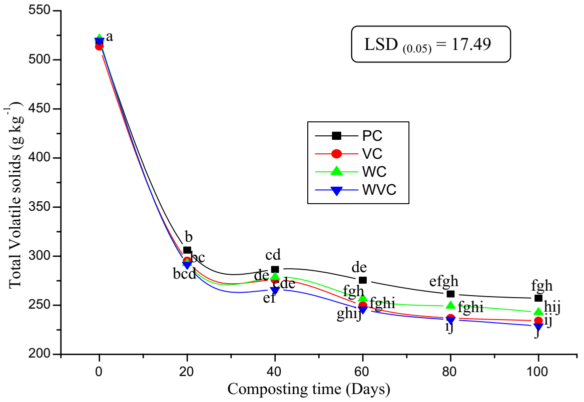

Fig. 10 Changes in total volatile solids of composting mixture in different composting methods with time (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at $P \leq 0.05$

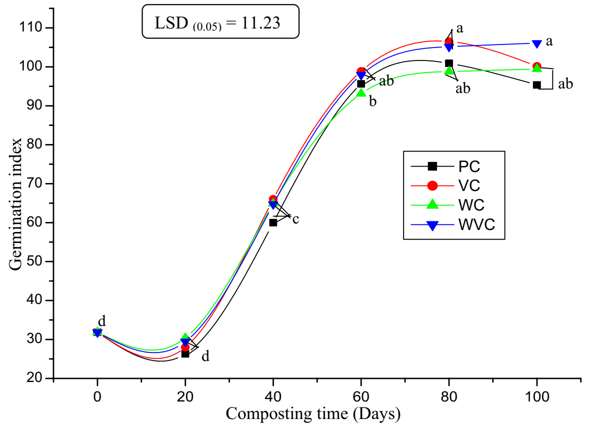

Fig. 11 Changes in germination index (GI) of composting mixture in different composting methods with time (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at $P \leq 0.05$

Tam (1998) also reported findings that are similar to the results of this study.

The reason for the low germination index value of in the initial sample and the sample taken at the 20th day of the composting process could be attributed to the presence of phytotoxic compounds in the raw wastes and their production in the substrate during the active phase of composting. Phytotoxic compounds, such as; ammonium ions, fatty acids, and low molecular weight phenolic acids are reported to impair seed germination and root elongation (Delgado 2010; Gómez-Brandón et al. 2008). It was also evident from the chemical analysis of the raw material and compost samples of this study that the highest level of ammonium was recorded at the 20th day of sampling followed by the initial substrate at day 0. The detrimental effect of high levels of ammonium to seed germination and root elongation was reported in many other studies (Tiquia and Tam 1998; Selim et al. 2012 and Guo et al. 2012).

The rise in GI late at the 60th day might be due to the degradation of the phytotoxic compounds which were present in the initial raw wastes or produced during the active phase of composting as intermediate products of microbial metabolism (Bernal et al. 1998). According to Haq et al. (2014) compost with GI of more than 80% is considered to be matured and practically free of phytotoxic substances. In this study as indicated in the graph (Fig. 11), all the treatments were found to have a GI value of >80% at the 60th day of sampling, implying that, about 60 days were needed to overcome the threshold limit of 80% by reducing the phytotoxicity of the compost to levels consistent for a safe soil application (Soares et al. 2013).

Pathogen inactivation

Total faecal coliforms

Except for VC all other methods of composting showed a substantial reduction in population of faecal coliforms at the 20th day of sampling. These treatments were effective in keeping the population of the faecal coliforms in the compost below the minimum allowable limit (<1000 cfu g^{-1}) right at the 20th day. The reduction in the population of faecal coliforms in these methods of composting might be related to the high temperature generated in the compost pile during the thermophilic phase. Perhaps in this study the first sampling was taken at the 20th day, but it is likely that these methods could have attained such low population even much earlier than the 20th day. As per the reports of WHO (2006) and Schönning and Stenström (2004), pathogen inactivation in composting is achieved when temperatures above 50 °C are maintained for at least 1 week. Temperatures exceeding 50 °C were also recorded in those methods (WC, PC and WVC) involving thermophilic phase of the current study.

Some inconsistencies in reduction pattern of the faecal coliforms were detected in WC during the mesophilic and curing phase, where the population of these pathogens came to rise and fall at different sampling periods (Fig. 12). This may be due to the contamination of the compost mass from the external source during the periodic and manual turning of the compost pile.

Regarding VC, contrary to the former methods, the number of the faecal coliforms was found to increase remarkably at the 20th day of sampling, this was then declined steadily during the subsequent sampling periods (Fig. 12). The increasing of faecal coliforms in VC during the 20th day of sampling could be attributed to creation of a good environment for multiplication of this pathogen through rehydration and subsequent availability of easily degradable substrates by dissolution following rehydration (Mupondi et al. 2010). The reports by Schönning and Stenström (2004) and WHO (2006) also indicated that certain types of pathogenic bacteria can increase in numbers when conditions favouring their growth are established in their storage medium/environment.

The reduction of the faecal coliforms population during the subsequent period of vermicomposting may be attributed to some activities of earthworms which possibly include: selective predation/consumption (Edward and Bohlen 1996; Kumar and Shweta 2011); mechanical destruction through action of gizzard (Edwards and Subler 2011); microbial inhibition through humic and coelomic acids or other enzymes secreted within the digestive tract (Edwards and Subler 2011); stimulation of microbial antagonists (Kumar and Shweta 2011); and indirectly through stimulation of endemic or other

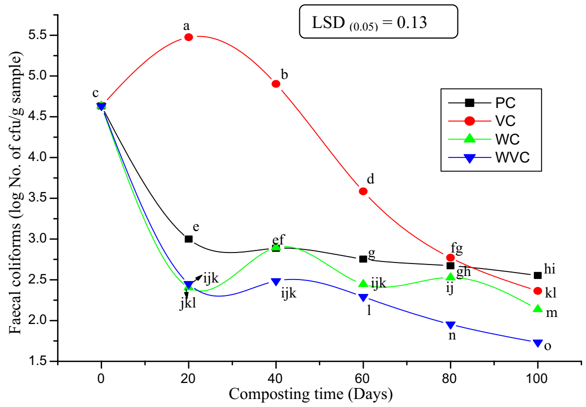

Fig. 12 Elimination of faecal coliform during co-composting of dried faecal sludge and municipal solid organic wastes with time. (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting). *Different letters* indicate significant differences at P ≤ 0.05

microbial species which outcompete, antagonize, or otherwise destroy pathogens (Edwards and Subler 2011).

Helminth egg count

During the composting process, there was a general reduction in the number of helminth eggs for all the treatments (Fig. 13). The total helminth egg count was found to decrease from 38.89 g^{-1} TS of the starting material to 8.33 (WC), 19.44(VC), 14.81 (PC) and 2.78 (WVC) in the final product as evidenced at the 100th day. These values correspond to a 78.57, 50, 61.9 and 92.86% total reduction of eggs for the respective treatments. It has been observed that the extent to which the helminth eggs were eliminated varied significantly with time and among the treatments ($P \leq 0.01$). Those treatments involving thermophilic composting (WC, PC and WVC) demonstrated a drastic reduction of eggs during the first 20 days of the process when the active thermophilic phase was prevailing. This amounts to 84.85% (WC), 73.08% (PC) and 74.36% (WVC) of the total reductions recorded in the respective treatments. Whereas the treatment without a thermophilic phases (VC), the greatest reduction of helminth eggs was observed during the latter stages of the composting process. More than 75% of the total reduction was recorded after the 60th day of the process while only 23.81% of it was recorded during the first 40 days of the composting process.

The highest reduction of eggs was achieved in WVC method followed by windrow method of composting (WC), while the sole vermicomposting method (VC) registered the lowest value (Fig. 13). However, only the former treatment (WVC) is complying with the WHO guidelines of <3–8 Ascaris egg g^{-1} TS while all the rest treatments were found to have egg counts more than the threshold limit. The result of this study clearly demonstrated that the high temperature produced in the thermophilic phase of the composting process is much more effective in sanitizing pathogenic parasites of faecal sludge than the earthworms did. It has been suggested that high temperature may increase the permeability of the Ascaris eggs' shell, allowing transport of harmful compounds, as well as increasing the desiccation rate of the eggs (Koné et al. 2010).

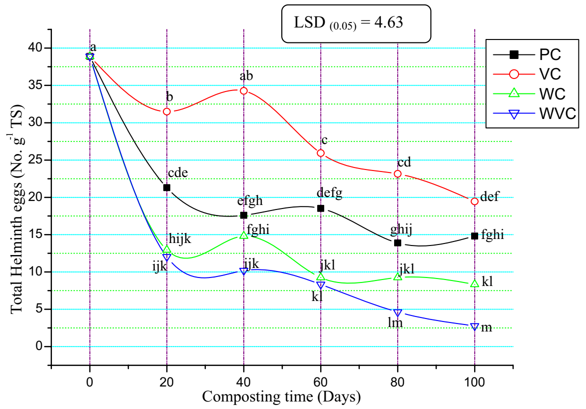

Fig. 13 Helminth eggs removal dynamics during co-composting of faecal sludge and municipal organic solid waste. (*WC* windrow composting, *VC* vermicomposting, *PC* pit composting, *WVC* combined windrow and vermicomposting *LSD* Least significant difference). Different letters indicate significant differences at $P \leq 0.05$

Even though numerous authors reported the full elimination of parasitic eggs under thermophilic condition (Plym-Forshell 1995; Gantzer et al. 2001), this had not come about in the present study where helminth eggs were still detected despite the fact that the thermophilic condition (≥45 °C) was maintained for about 15–19 days. It is likely that the lethal temperature, being not evenly distributed throughout the piled biomass, the complete destruction of the eggs may not be ensured. The substrates that lay on the top of the pile, being exposed to the open atmosphere, might have experienced a relatively cooler temperature than the inner laid ones. Strauch (1991) suggested that composting ensures hygienization of the material on condition that all biomass is exposed to a sufficiently high temperature (55 °C for 14 days).

The temperature reading of the present study indicates that, on average, a high temperature of (>55 °C) was recorded only for 8 days in windrows and during which the pile was turned only once letting it to experience the high temperature of >55 °C for only a day after this first turning. This would therefore suggest that, had the piled feedstock been turned more frequently such that every 2 or 3 days, the biomass would have enjoyed the lethal high temperature uniformly and for relatively longer period of time and thus would have resulted in increased efficiency of helminth egg elimination. This justification is of course in argument with the reports of Koné et al. (2007) who demonstrated the non-significant effect of turning frequency on the inactivation efficiency of helminths egg. However, it has been explained that the size of the piled feedstock determines the magnitude of heat generated and the time duration in which the thermophilic phase would be maintained during the composting process. The larger the size of the pile the higher the magnitude of heat generated and the longer the thermophilic phase would be maintained within the pile, and thus the less frequently it can be turned. In cases where the pile size is smaller, the thermophilic phase would last for a short period of time; therefore, unless turned frequently there would be no chance for the out laid biomass to enjoy the lethal high temperature which is usually formed inside the pile. In the United States of America, the compost is regarded as hygienically safe if a temperature >55 °C is maintained in windrows for at least 15 days with a minimum of 5 turnings during the high temperature period (USEPA 1999).

Conclusions

The biodegradation process of organic wastes is markedly influenced by the methods of composting employed. Turned windrows (WC) and composting involving earthworms (VC and WVC) hasten the biodegradation process of organic wastes and result in the production of stable compost earlier than the traditional pit method of composting (PC). Even though all the tested methods of composting remarkably reduced the pathogenic organisms (faecal coliforms and helminth eggs), it was only the WVC method that qualify the standard set by WHO, keeping the concentration of helminth egg below the threshold level. Thus, elimination of pathogens from composts being a critical consideration, this study would recommend the WVC method for composting organic wastes involving human excreta.

Additional file

Additional file 1. Table S1 Mean daily temperature values of different composting methods

Abbreviations

ANOVA: analysis of variance; CFU: colony forming unit; DFS: dried faecal sludge; EC: electrical conductivity; GI: germination index; FS: faecal sludge; MSW: municipal solid waste; OC: organic carbon; PC: pit composting; TN: total:nitrogen; TVS: total volatile solids; USEPA: United States Environmental Protection Agency; VC: vermicomposting; WC: windrow composting; WVC: windrow plus vermicomposting; WHO: world health organization.

Authors' contributions

TM conceived and carried out the study; performed the analyses and drafted the manuscript. HG participated in the design of the study; KK, KW, BS and HY participated in the design of the study supervised the analysis process and helped draft the manuscript. All authors read and approved the final manuscript.

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Acknowledgements

This study was financially supported by the Ministry of Education of the Federal Democratic Republic of Ethiopia. Authors wish to thank the Sanitation and Beautification Agency (SBA) and Water Supply and Sewerage Authority (WSSA) of Dire Dawa City Administration for their cooperation in collecting and providing the compostable material.

Competing interests

The authors declare that they have no competing interests

Received: 13 May 2016 Accepted: 1 January 2017

References

Ayres RM, Mara DD (1996) Analysis of wastewater for use in agriculture—a laboratory manual of parasitological and bacteriological techniques. World Health Organization (WHO), Geneva

Beneberu S, Eline B, Harole Y, Zelalem L (2012) Current solid waste management practices for productive reuse in Dire Dawa City, Ethiopia (Draft project Report)

Bernal MP, Paredes C, Sanchez-Monedero MA, Cegarra J (1998) Maturity and stability parameters of composts prepared with a wide range of organic wastes. Bioresour Technol 63:91–99

Bernal MP, Alburquerque JA, Moral R (2009) Composting of animal manures and chemical criteria for compost maturity assessment: a review. Bioresour Technol 100:5444–5453

Bjorklund A (2002) The potential of using thermal composting for disinfection of separately collected faeces in Cuernacava, Mexico. Minor Field Studies No. 200. Swedish University of Agricultural Sciences, International Office. ISSN 1402-3237

Bowman DD, Liotta JL, McIntosh M, Lucio-Forster A (2006) Ascaris suum egg inactivation and destruction by the vermicomposting worm, *Eisenia foetida*. Residuals Biosolids Manag 2:11–18

Bremner JM, Mulvaney CS (1982) Nitrogen—total. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis, Part 2. Chemical and Microbiological Properties. Agronomy Monograph No. 9. ASA-SSSA, Madison, Wisconsin, USA, pp 595–624

Brewer LJ, Sullivan DM (2003) Maturity and stability evaluation of composted yard trimmings. Compost Sci Util 11(2):96–112

Bundela PS, Gautam SP, Pandey AK, Awasthi MG, Sarsaiya S (2010) Municipal solid waste management in Indian cities—a review. Int J Environ Sci 1(4):591–606

Carr L, Grover R, Smith B, Richard T, Halbach T (1995) Commercial and on-farm production and marketing of animal waste compost products. In: Steele K (ed) Animal waste and the land–water interface. Lewis Publishers, Boca Raton, pp 485–492

Community Development Research (2011) Ethiopia solid waste and landfill (country profile and action plan). Global Methane Initiative http://www.globalmethane.org/. Accessed on August 2012

Cooperband LR, Stone AG, Fryda MR, Ravet JL (2003) Relating compost measures of stability and maturity to plant growth. Compost Sci Util 11(2):113–124

Delgado M (2010) Phytotoxicity of uncomposted and composted poultry manure, African. J Plant Sci 4:154–162

Dias BO, Silva CA, Higashikawa FS, Roig A, Sánchez-Monedero MA (2010) Use of biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification. Bioresour Technol 101:1239–1246

Domínguez J, Edwards CA (2010) Relationships between composting and vermicomposting: relative values of the products. In: Edwards CA, Arancon NQ, Sherman RL (eds) Vermiculture technology: earthworms, organic waste and environmental management. CRC Press, Boca Raton, pp 1–14

Dominguez J, Edwards CA, Subler S (1997) Comparison of vermicomposting and composting. Bio-Cycle 38(4):57–59

Dumitrescu L, Manciulea I, Sauciuc A, Zaha C (2009) Obtaining fertilizer compost by composting vegetable waste, sewage sludge and sawdust. In: Bulletin of the Transilvania, vol 2, no 51. University of Braşov, pp 117–122

Eastman BR, Kane PN, Edwards CA, Trytek L, Gunadi B, Stermer AL, Mobley JR (2001) The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. Compost Sci Util 9(1):38–49

Edward CA, Bohlen PJ (1996) Biology and ecology of earthworms. Chapman and Hall, London

Edwards CA, Subler S (2011) Human pathogen reduction during vermicomposting. In: Edwards CA, Arancon NQ, Sherman R (eds) Vermiculture technology Florida. CRC Press Taylor and Francis Group, Florida, pp 249–261

Epstein E (1997) The science of composting. Technomic Publishing Company Inc, Lancaster

Finstein MS, Miller FC, Strom PF (1986) Monitoring and evaluating composting process performance. J Water Pollut Control Fed 58(4):272–278

Forster JC, Zech W, Wiirdinger E (1993) Comparison of chemical and microbiological methods for the characterization of the maturity of composts from contrasting sources. Biol Fertil Soils 16:93–99

Frederickson J, Butt KR, Morris RM, Daniels C (1997) Combining vermiculture with traditional green waste composting systems. Soil Biol Biochem 29(3/4):725–730

Frederickson J, Howell G, Hobson AM (2007) Effect of pre-composting and vermicomposting on compost characteristics. Eur J Soil Biol 43:S320–S326

Gallizzi K (2003) Co-composting reduces helminth eggs in faecal sludge: a field study in Kumasi, Ghana. SANDEC, Dübendorf, p 45

Gantzer C, Gaspard P, Galvez L, Huyard A, Dumouthier N, Schwartzbrod J (2001) Monitoring of bacteria and parasitological contamination during various treatment of sludge. Water Resour 35(16):3763–3770

Gao M, Liang F, Yub A, Li B, Yang L (2010) Evaluation of stability and maturity during forced-aeration composting of chicken manure and sawdust at different C/N ratios. Chemosphere 78:614–619

Garcia C, Hernandez T, Costa F (1993) Evaluation of the organic matter composition of raw and composted municipal wastes. Soil Sci Plant Nutr 39:99–108

Gómez-Brandón M, Lazcano C, Domínguez J (2008) The evaluation of stability and maturity during the composting of cattle manure. Chemosphere 70:436–444

Guo R, Li G, Jiang T, Schuchardt F, Chen T, Zhao Y, Shen Y (2012) Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. Bioresour Technol 112:171–178

Haq T, Ali TA, Begum R (2014) Seed germination bioassay using maize seeds for phytoxicity evaluation of different composted materials. Pak J Bot 46(2):539–542

Hill GB, Lalander C, Baldwin SA (2013) The effectiveness and safety of vermi-versus conventional composting of human feces with *Ascaris suum* ova as model helminthic parasites. J Sustain Dev 6(4):1–10

Hock LS, Baharuddin AS, Ahmed MN, Md. Shah UK, Abdul Rahaman NA, Abd-Aziz S, Hassan MA, Shirai Y (2009) Physicochemical changes in windrow co-composting process oil palm mesocarpfiber and palm oil effluent anaerobic sludge. Aust J Basic Appl Sci 3(3):2809–2819

http://www.cfe.cornell.edu/compost/invertebrates.html (1 of 4) [1/16/2001 8:49:10 AM]. Cornell composting Science and Engineering

Huang GF, Fang M, Wu QT, Zhou LX, Liao XD, Wong JWC (2001) Co-composting of pig manure with leaves. Environ Technol 22:1203–1212

Iqbal MK, Khan RA, Nadeem A, Hussnain A (2012) Comparative study of different techniques of composting and their stability evaluation in municipal solid waste. J Chem Soc Pak 34(2):273–282

Jusoh ML, Manaf LA, Abdul Latif P (2013) Composting of rice straw with effective microorganisms (EM) and its influence on compost quality. Iran J Environ Health Sci Eng 10:17

Khwairakpam M, Kalamdhad AS (2011) Vermicomposting of vegetable wastes amended with cattle manure. Res J Chem Sci 1(8):49–56

Koné D, Cofie O, Zurbru C, Gallizzi K, Moser D, Drescher S, Strauss M (2007) Helminth eggs inactivation efficiency by faecal sludge dewatering and co-composting in tropical climates. Water Res 14(9):4397–4402

Koné D, Cofie O, Nelson K (2010) Low-cost options for pathogen reduction and nutrient recovery from faecal sludge. In: Drechsel P, Scott CA, Raschid-Sally L, Redwood M, Bahri A (eds) Wastewater irrigation and health: assessing and mitigating risk in low-income countries. International Water Management Institute (IWMI), Earthscan, International Development Research Centre (IDRC), Colombo, pp 171-188.

Kumar R, Shweta (2011) Removal of pathogens during vermi-stabilization. J Environ Sci Technol 4(6):621–629

Kumar PR, Jayaram A, Somashekar RK (2009) Assessment of the performance of different compost models to manage urban household organic solid wastes. Clean Technol Environ Policy 11:473–484

Lazcano C, Gómez-Brandón M, Domínguez J (2008) Comparison of the effectiveness of composting and vermicomposting for the biological stabilization of cattle manure. Chemosphere 72:1013–1019

Levanon D, Pluda D (2002) Chemical, physical and biological criteria for maturity in composts for organic farming. Compost Sci Util 10(4):339–346

Lung AJ, Lin CM, Kim JM, Marshall MR, Nordstedt R, Thompson NP, Wei CI (2001) Destruction of *Escherichia coli* O157:H7 and *Salmonella enteritidis* in cow manure composting. J Food Prot 64:1309–1314

Maso MA, Blasi AB (2008) Evaluation of composting as a strategy for managing organic wastes from a municipal market in Nicaragua. Bioresou Technol 99:5120–5124

Monroy F, Aira M, Domínguez J (2008) Changes in density of nematodes, protozoa and total coliforms after transit through the gut of four epigeic earthworms (Oligochaeta). Appl Soil Ecol 39:127–132

Mupondi LT, Mnkeni PNS, Brutsch MO (2006) The effects of goat manure, sewage sludge and effective microorganisms on the composting of pine bark. Compost Sci Util 14:201–210

Mupondi LT, Mnkeni PN, Muchaonyerwa P (2010) Effectiveness of combined thermophilic composting and vermicomposting on biodegradation and sanitization of mixtures of dairy manure and waste paper. Afr J Biotechnol 9(30):4754–4763

Ndegwa PM, Thompson SA (2001) Integrating composting and vermicomposting in the treatment and bioconversion of solids. Bioresour Technol 76:107–112

Niwagaba C, Nalubega M, Vinnerås B, Sundberg C, Jonsson H (2009) Bench-scale composting of source-separated human faeces for sanitation. Waste Manag 29:585–589

Okalebo JR, Guthua KW, Woomer PJ (2002) Laboratory methods of soil and plant analysis—a working manual. TSBF-CIAT and SACRED Africa, Nairobi

Padmavathiamma PK, Li LY, Kumari UR (2008) An experimental study of vermin biowaste composting for agricultural soil improvement. Bioresour Technol 99:1672–1681

Pisa C, Wuta M (2013) Evaluation of composting performance of mixtures of chicken blood and maize stover in Harare, Zimbabwe. Int J Recycl Org Waste Agric 2(5):1–11

Plym-Forshell L (1995) Survival of *Salmonellas* and *Ascarissuum* eggs in a thermophilic biogas plant. Acta Vet Scandinavica 36:79–85

Rao KJ (2007) Composting of municipal and agricultural wastes. In: Proceedings of the international conference on sustainable solid waste management, Chennai, India, 5–7 September 2007

Rodriguez-Canche LG, Cardoso-Vigueros L, Maldonado-Montiel T, Martinez Sanmiguel M (2010) Pathogen reduction in septic tank sludge through vemicomposting using *Eisenia fetida*. Bioresour Technol 101:3548–3553

Schönning C, Stenström TA (2004) Guidelines for the safe use of urine and faeces in ecological sanitation. Report 2004-1. Ecosanres, SEI. Sweden. www.ecosanres.org

Schwartzbrod J (2003) Quantification and viability determination for helminth eggs in sludge (modified EPA method 1999). University of Nancy, Nancy

Seal A, Bera R, Chatterjee AK, Dolui AK (2012) Evaluation of a new composting method in terms of its biodegradation pathway and assessment of compost quality, maturity and stability. Arch Agron Soil Sci 58(9):995–1012

Selim SM, Zayed MS, Atta MH (2012) Evaluation of phytotoxicity of compost during composting process. Nat Sci 10(2):69–77

Smith DC, Hughes JC (2002) Changes in chemical properties and temperature during the degradation of organic wastes subjected to simple composting protocols suitable for small-scale farming, and quality of the mature compost. S Afr J Plant Soil 19:53–60

Soares MR, Matsinhe C, Belo S, Quina MJ, Quinta-Ferreira R (2013) Phytotoxicity evolution of biowastes undergoing aerobic decomposition. J Waste Manag. doi:10.1155/2013/479126

Soumaré M, Demeyer A, Tack FMG, Verloo MG (2002) Chemical characteristics of Malian and Belgian solid waste composts. Bioresour Technol 81:97–101

Strauch D (1991) Survival of pathogenic micro-organisms and parasites in excreta, manure and sewage sludge. Revue Sci Tech (Int Off Epizoot) 10:813–846

Sundberg C, Smars S, Jonsson H (2004) Low pH as an inhibiting factor in the transition of mesophilic to thermophilic phase in composting. Bioresour Technol 95:145–150

Tiquia SM, Tam NFY (1998) Elimination of phytotoxicity during co-composting of spent pig-manure sawdust litter and pig sludge. Bioresour Technol 65:43–49

Tiquia SM, Richard TL, Honeyman MS (2002) Carbon, nutrient, and mass loss during composting. Nutr Cycl Agroecosyst 62:15–24

Tognetti C, Loas F, Mazzarino MJ, Hernandez MT (2005) Composting vs. vermicomposting: a comparison of end product quality. Compost Sci Util 13(1):6–13

Tognetti C, Mazzarino MJ, Laos F (2007) Improving the quality of municipal organic waste compost. Bioresour Technol 98:1067–1076

USEPA (United States Environmental Protection Authority) Pathogen Equivalency Committee (PEC) (1999) Control of pathogens and vector attraction in sewage sludge. In: USEPA Environmental Regulations and Technology, Office of Research and Development EPA/625/R-92/013, Washington, DC, p 177

Vinnerås B (2007) Comparison of composting, storage and urea treatment for sanitising of faecal matter and manure. Bioresour Technol 98:3317–3321

Vuorinen AH, Saharinen MH (1997) Evolution of microbiological and chemical parameters during manure and straw co-composting in a drum composting system. Agric Ecosyst and Environ 66:19–29

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter and proposed modification of the titration method. Soil Sci Soc Am J 37:29–34

WHO (2006) Guidelines for the safe use of wastewater, excreta and greywater, vol 4. Excreta and grey water use in agriculture. ISBN: 92 4 154685 9

Witter E, Lopez-Real J (1988) Nitrogen losses during the composting of sewage sludge, and the effectiveness of clay soil, Zeolite and compost in adsorbing volatilised ammonia. Biol Wastes 23:279–294

Wu L, Ma LQ, Martinez GA (2000) Comparison of methods for evaluating stability and maturity of bio-solids compost. J Environ Qual 29(2):424–429

Xanthoulis D, Strauss M (1991) Reuse of wastewater in agriculture at Ouarzazate, Morocco (Project UNDP/FAO/WHO MOR 86/018). Unpublished mission reports

Yadav KD, Tare V, Ahammed MM (2010) Vermicomposting of source separated human faeces for nutrient recycling. Waste Manag 30:50–56

Yadav KD, Tare V, Ahammed MM (2012) Integrated composting–vermicomposting process for stabilization of human faecal slurry. Ecol Eng 47:24–29

Zmora-Nahum S, Markovitch O, Tarchitzky J, Chen Y (2005) Dissolved organic carbon (DOC) as a parameter of compost maturity. Soil Biol Biochem 37:2109–2116

Zucconi F, de Bertoldi M (1987) Compost specification for the production and characterization of compost from municipal solid waste. In: de Bertoldi M, Ferranti MP, Hermite PL, Zucconi F (eds) Compost: production, quality and use. Elsevier Applied Science Publishers, Barking, pp 30–50

Zucconi F, Forte M, Monaco A, De Bertoldi M (1981) Biological evaluation of compost maturity. Biocycle 22(4):27–29